A New Culprit in the Second Parameter Problem in the Sculptor Dwarf Spheroidal Galaxy?

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ABSTRACT

Color-magnitude diagrams from deep, wide-field CCD photometry of the Sculptor dwarf spheroidal galaxy reveal that the red horizonal branch (RHB) stars are strongly concentrated towards the center of the galaxy relative to the dominant old population in Sculptor, confirming an earlier claim of such a gradient (Da Costa et al. 1996). Since we find no radial gradients of the age or metallicity distribution within Sculptor, neither age nor metallicity can individually account for the internal 'second parameter' problem observed within the galaxy. We have also identified an unusual 'spur' of stars that extends from the main sequence turnoff region and located between the canonical blue straggler region and the subgiant branch. These stars are also more centrally concentrated than the oldest stars in Sculptor, although not as extremely as the RHB stars. Unable to convincingly interpret the spur either as an unusual young population or as a foreground population of stars, we conclude that binary stars offer the most reasonable explanation for the origin of the spur that is also consistent with other features in the CMD of Sculptor. We infer that 30-60% of all apparently single stars in the inner region of Sculptor may be binaries. We speculate that the possible radial gradient in the binary-star population may be related to the variation of the HB morphology in Sculptor.

Subject headings: galaxies: evolution, galaxies: stellar content, galaxies: individual (Sculptor dwarf)

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1. Introduction

The dwarf spheroidal (dSph) companions of the Milky Way have proven to be useful laboratories to study the remarkable range of star-formation histories (SFH) that can occur on the smallest galaxian scales (e.g. Carina, Fornax, Leo I; see Mateo 1998 and references therein; also Grebel 1997). Ironically, the first dSph galaxy to be discovered – Sculptor (Scl; Shapley 1938) – has long been believed to have experienced the relatively sedate star-formation history (SFH) that was initially attributed to all dSph galaxies (Da Costa 1984; Kaluzny et al. 1995). The recent discovery of neutral gas associated with Scl (Carignan et al. 1998) suggests a more complex history. Past photometric studies of Scl have either been too shallow or covered too little area to study the spatial variations of *all* stellar populations in the galaxy. We therefore set out to obtain deep, wide-field CCD photometry to derive a complete SFH of Scl (c.f. Stetson et al. 1998), particularly in regions near the newly-discovered gas. A second paper will present detailed results of a comprehensive analysis of the SFH of Scl (c.f. Hurley-Keller et al. 1998).

This *Letter* is motivated by two unexpected findings. First, we observe that the red horizontal-branch (RHB) stars in Scl are significantly more centrally concentrated than any other stellar component of the galaxy, confirming earlier suggestions of such a gradient (Da Costa et al. 1996; Majewski et al. 1999). Second, we have identified an unusual sequence of stars that extends from the main-sequence turnoff (MSTO) between the region containing blue stragglers (BS)/intermediate-age stars and the subgiant branch stars. We describe these features and offer a preliminary discussion of their possible origins and implications.

2. Observations

The photometry was obtained with the Big Throughput Camera (BTC; Wittman et al. 1998; see `www.astro.lsa.umich.edu/btc/tech.html` for details) at the CTIO 4m telescope on 1998 September 24. The camera contains four CCDs that each cover $14.7' \times 14.7'$ covering a total field of about 0.25 deg^2 with a pixel size of $0.43''$. For the principal observations discussed here, CCD 4 (located at the SW corner of the BTC) was centered on Scl and covered the entire inner region. The remaining three CCDs were centered 20-28 arcmin from the center of the galaxy, well outside the core radius of 5.8 arcmin (Irwin & Hatzidimitriou 1995). We refer to these observations as 'pointing 1'. We also obtained a few frames with Scl centered on CCD 2; we refer to these as 'pointing 2'. All data were obtained using the standard CTIO Johnson B and Kron-Cousins R filters.

We applied standard processing and reduction techniques (with DoPHOT; Schecter et al. 1993) to the images. The present results are based on photometry measured from deep images produced from the sum of all exposures in each filter (a total of 7200 sec in each filter). We have 10 stars in common with Da Costa (1984) results; our photometry is systematically consistent with this earlier study. For unknown reasons, the photometry from CCD 2 is significantly poorer than for the other CCDs. Apart from one test described below, we have chosen not to use the photometry from that chip in this study.

3. The Color-Magnitude Diagrams

Figure 1 shows the CMDs of the central $\sim 15' \times 15'$ region of Scl (from CCD 4), and of the outer region (combined results from CCDs 1 and 3). Nearly 70,000 stars are present in the 'inner' CMD and about 20,000 in the 'outer' CMD. Both CMDs exhibit a blue horizontal branch (BHB), a red giant branch (RGB), a well-defined subgiant branch (SGB), an old ($\sim$ 15 Gyr) MSTO, and a significant number of relatively blue, luminous stars which could either be canonical blue stragglers (see Piotto et al. 1999 for examples) or intermediate-age stars in Scl.

The CMDs show that the well-populated red horizontal branch (RHB) observed in the central region has essentially vanished in the outer region. Da Costa et al. (1996) have observed similar HB gradients in other dSph systems, and had suggested based on the Gunn system CCD photometry of Light (1988) that the HB population in Scl exhibits such a gradient. This effect has also been reported by Majewski et al. (1999). Our new data unambiguously confirm the existence and sense of the gradient (see Figure 1). The central CMD also clearly contains a feature unlike any seen in deep CMDs of other dSph galaxies: a well-populated 'spur' of stars extending ~ 0.7 mag above the old MSTO.

We can quantify the spatial distributions of the Scl populations using star counts. Figure 2a illustrates the locations of five regions sampling distinct populations within the CMD, as well as a sixth region in which false stars were added (see section 4). The boundaries of the BS, Spur, and SGB boxes ensure that the relative completeness in each one are similar. Table 1 lists the star counts in the CMD boxes as well as relevant ratios of the star counts. Because the CMDs of the outer CCDs do not differ significantly (CCD 2 excepted), the star counts for chips 1 and 3 were combined to improve the signal-to-noise of the outer-region counts. We assume Poisson uncertainties throughout this paper, and we consider a result to be 'significant' if the compared values differ by more than three times their combined uncertainties (i.e. $\Delta \geq 3$). We also employ the T2 statistic used by Da Costa et al. (1996) to compare count ratios. Table 1 confirms the visual impression of

Figure 1; relative to the old subgiant stars, there are five times as many RHB stars in the center as in the outer regions (RHB/SGB). The spur stars are the only other population to reveal any evidence of an over-concentration in the center of Scl.

The gradient in the HB morphology is not due to a simple age or metallicity gradient between the inner and outer regions. The magnitude and color of the old MSTO in both CMDs are the same to within 0.05 magnitudes, allowing at most a 1-2 Gyr variation in the mean age of the older turnoff component for a constant metallicity. While the color spread of the SGB reveals a clear metallicity dispersion (confirming the finding of Majewski et al. 1999), we find no evidence that the *mean* color of SGB stars differs between the inner and outer regions by more than 0.02 mag. Nor does the shape of the distribution vary; the ratios of blue to red SGB stars between the inner and outer regions show no statistically significant gradient from the inner to outer fields. We conclude that neither an age nor a metallicity gradient can individually account for the observed radial gradient of the HB morphology of Scl.

4. The Nature of the Spur

We have explored a number of interpretations to account for the spur stars, which have never been seen in any other dSph system and which may be related to the RHB gradient.

1. Are the spur stars photometric blends? The median FWHM of spur stars in the inner field is ~ 1.2 arcsec, identical to that of SGB and BS stars of similar brightness in that field; their appearance is also similar. They are distributed in the same way as all other stars and so are not associated with some particular structure or defect in the CCD. We also reduced the shallower, noisier data for pointing 2. The resulting CMD of the inner field has the same features as that derived from pointing 1. The same stars located in the spur in pointing 1 are still spur stars in pointing 2.

We added to the images 1500 false stars (100 stars at a time) drawn from an isochrone corresponding to the oldest population in Scl and a Salpeter-like IMF. The region labeled "Old" in Figure 2a samples a portion of this isochrone. We then compared the number of false Spur stars to the number of false Old stars. For every 100 stars from the false star sample detected in the Old region, 7 objects were detected in the Spur region; for the data, 19 Spur stars were detected for every 100 Old stars. At that rate, photometric blends could only account for a minority of the real spur stars ($\sim$30-40% = 7/19). Unlike the genuine spur stars, visual inspection of the false spur star images clearly shows them all to be photometric blends. We conclude that most of the spur stars of the inner field are not the result of image blending or other instrumental effects.

Similar tests in the outer region produced only 3 spur stars for every 100 Old stars. If we correct the inner and outer Spur/SGB proportions for blends, we still dectect a radial gradient of the relative number of spur stars based on both statistical criteria in Table 1. While the gradient in spur star counts (only a factor of ~ 2) is substantially less than that of the RHB stars, this is nonetheless circumstantial evidence that the spur may play some role, albeit uncertain, in producing the strong HB gradient in Scl.

2. Is the spur a sequence of young stars in Scl? Figure 2b compares our data with a variety of Padua isochrones (Bertelli et al. 1994) plotted to 'fit' the oldest main sequence stars and the stars in the BS region. We assumed a metallicity of $z = 0.0004$, a solar abundance distribution, and a distance modulus of 19.5, values consistent with previous studies of Scl (Da Costa 1984; Grebel et al. 1994; Kaluzny et al. 1995; Majewski et al. 1999). We neglect the foreground extinction towards Scl ($A_V \lesssim\ 0.05 \pm 0.05$ mag; Mateo 1998).

The oldest stars in Scl can be fit with models corresponding to ages of about 14-15 Gyr, while the BS region can be adequately described as a sequence of intermediate-age stars older than about 4-5 Gyr. We then tried to fit an intermediate-age model to the spur. For the same metallicity/distance parameters, we found that the R-band luminosity of the 'turnoff' of the spur corresponds to an age of about 6-8 Gyr. The corresponding isochrone represents the color of the spur very poorly (Fig. 2b). If we instead match the spur's 'turnoff' color, we require a more metal-rich, younger isochrone. This model (dashed line) predicts a sparse RGB to the red of the principal RGB, similar to a feature seen in the CMD of the Sagittarius dSph galaxy (Sarajedini & Layden 1995), which is certainly absent in Scl. We conclude that the spur is not the turnoff region of a normal intermediate-age stellar population.

3. Is the spur associated with a foreground object? A 15 Gyr isochrone with z=0.0004 but an assumed distance modulus of 18.8 fits the spur reasonably well (Figure 2c). Unfortunately, this good fit is achieved at the cost of a highly contrived scenario. We would require that the putative foreground object has an old stellar population identical to that of Scl, but is located ~ 20 kpc in front of the galaxy directly along the line of sight between Earth and the center of Scl. If the foreground component were aligned instead along the line connecting Scl and the Galactic center (Piatek & Pryor 1995; Kroupa 1997), we would expect it to be offset by up to 2 degrees from the center of Scl as seen from the Sun. There is also no hint of a corresponding red or blue HB component located ~ 0.7 mag above the observed HB stars in Scl that could be associated with the old component of the foreground system.

4. Is the spur a photometric binary sequence? We used the population synthesis code from Padua (Bertelli et al., private communication) to carry out preliminary simulations of a binary star population in Scl. Input parameters include the binary fraction (f, the fraction of apparently single stars that are truly binary systems) and the range of binary mass ratios (q, where $0.0 < q \leq 1.0$). The stars which become binaries and their masses are chosen randomly from uniform distributions of these parameters. The models do not reproduce effects from binary interactions or mass transfer.

Our simulations adopted f in the range 0.30 to 0.95 for binary populations with $q \geq 0.7$ to $q \geq 0.95$. The best fits to the data require $f \sim$ 30-60% and a distribution of mass ratios with most binaries having $q \gtrsim 0.7$. The quality of the fits was determined by comparing the color distribution and luminosity function of the data and the models in the spur region, and across the subgiant branch (e.g. Hurley-Keller et al. 1998). Models with $f \gtrsim 0.6$, for example, begin to predict too many spur stars relative to the number of subgiant stars, while models with too few binaries with $q \sim 1.0$ do not extend as far above the old MSTO as observed. An example of a model with binaries is shown in Figure 2d.

These preliminary models certainly do not provide a perfect match to the data; for example, we are unable to reproduce the relatively narrow color distribution of the observed spur. Alternative mass ratio and period distributions, the inclusion of mass transfer effects, or the effects of binary coalescence could all significantly modify the model results. We plan to explore these effects in our detailed analysis of these data. Nonetheless, we conclude that the interpretation of the spur as primarily a binary sequence represents the only viable interpretation of this feature.

5. Discussion

Scl has long been known to have an anomolously red HB for its predominantly old age and low metallicity (Zinn 1980; Da Costa 1984; Mateo 1998). Our observations confirm that this 'second parameter effect' is present, but only in the inner region of the galaxy. Oddly, we cannot easily attribute the HB morphology gradient to the usual suspects; our main-sequence photometry reveals no significant age or metallicity gradients within Scl. If confirmed by spectroscopic abundance determinations, this conclusion casts doubt on the reliability of the HB as an age indicator of old and intermediate-age populations (e.g. Da Costa et al. 1996; Mateo 1998). In Scl, we can speculate that the HB morphology may be related in some way to the binary component of Scl, the only other population to show *any* radial gradient. Alternatively, a metallicity gradient may be present but restricted to a limited number of elements that do not strongly affect broad-band colors of evolved stars (Majewski et al. 1999). A final possibility is that Scl does exhibit age and metallicity variations, but these largely cancel out in the broad-band colors for all evolutionary stages. We shall investigate this (unlikely) possibility in our detailed study of the SFH of Scl.

Binaries have previously been detected both spectroscopically (Queloz & Dubath 1995, Armandroff & Da Costa 1986) and kinematically (Olszewski et al. 1996, Armandroff et al. 1995, Hargreaves et al. 1996) in dSph systems. Recently, using HST photometry, Gallart et al. (1999) found that a significant binary population was needed to explain the detailed morphology of the CMD of Leo I. The complex and temporally extended SFH of that galaxy made it impossible to disentangle the effects of age and binaries unambiguously. Likewise, in other dSph with strong intermediate-age components such as Carina or Fornax, these binaries would be difficult to isolate and would complicate the interpretation of the CMD. With its simpler SFH, Scl provides a cleaner environment to study its binary population photometrically.

The relatively high inferred binary fraction does not conflict with the low observed spectroscopic binary fraction of 10-20% (Queloz et al. 1995; Hut et al. 1992). It also probably does not significantly alter conclusions regarding galactic masses based on the kinematics derived from single-epoch radial velocity measurements of red giants (Olszewski et al. 1996; Hargreaves et al. 1996) unless the mass-ratio distribution is very strongly skewed towards unity. This sort of distribution seems unlikely in Scl. Although we infer a significant number of $q \sim 1.0$ binaries, models containing exclusively equal-mass binaries do not reproduce our photometric observations of Scl well.

The central over-concentration of spur stars/binaries towards the center of Scl may be an important clue in understanding the formation and evolution of this galaxy. Since mass segregation is implausible given the relaxation time for this low-density system, the segregation of binary/RHB stars could be the relic of a time of violent relaxation, of the accretion of independent systems, or of some formation process that extended well beyond the present-day boundaries of the luminous component of the galaxy. Consequently, systems with complex substructure such as Fornax (Stetson et al. 1998; see also Eskridge 1988a,b) and now possibly Scl may contain distinct dynamical components. Along with deep, wide-field photometry and spectroscopic abundances, large-scale spectroscopic studies of the kinematics of these galaxies will help disentangle the detailed histories of these deceptively complicated galaxies.

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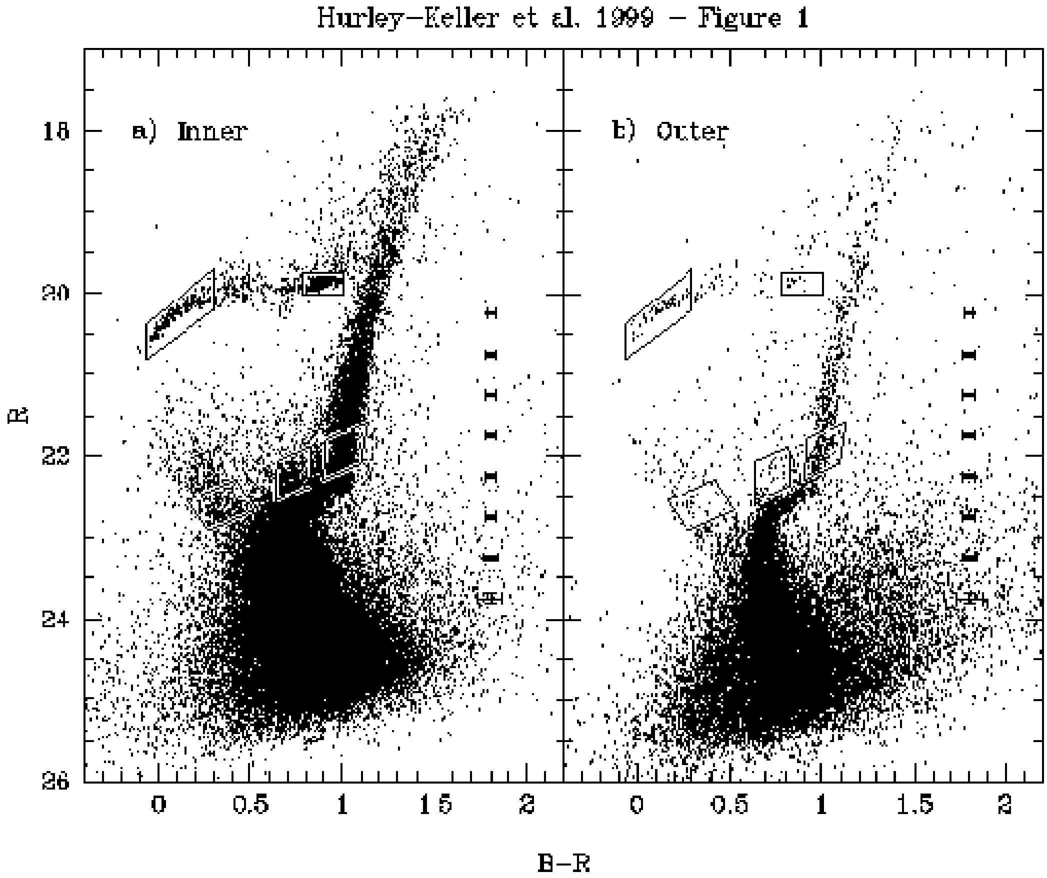
Fig. 1.— Color-magnitude diagrams of the inner and outer regions of Scl with boxes for reference(see text). Panel a): CMD of the inner region of Scl with more than 70,000 stars. Panel b): CMD of the outer region of Scl containing about 30,000 stars.

Fig. 2.— Possible scenarios to explain the "spur". Panel a): the inner CMD with boxes (see text). Panel b): the inner CMD with isochrones. The solid lines show good fits to the old MSTO (14 Gyr), the spur (8 Gyr), and the young/BS stars ($\geq$4 Gyr) for z=0.0004 and a distance modulus of 19.5. The long-short dash line is an isochrone with z=0.0006 and age=8 Gyr. The dashed line is an isochrone with z=0.004 and age=4 Gyr. Panel c): the inner CMD with a 15 Gyr, z=0.0004 isochrone at a distance modulus of 18.8. Panel d): A simulated CMD with an old population of 15 Gyr with 30% of the apparent single stars as binaries with a mass fraction $q \geq$0.7, and a young population generated from a constant SFR from 15 Gyr to 4 Gyr old. Both populations have z=0.0004.



Hurley–Keller et al. 1999 – Figure 1
a) Inner
b) Outer
R
B–R
18
20
22
24
26
0
0.5
1
1.5
2

Hurley-Keller et al. 1999 – Figure 2

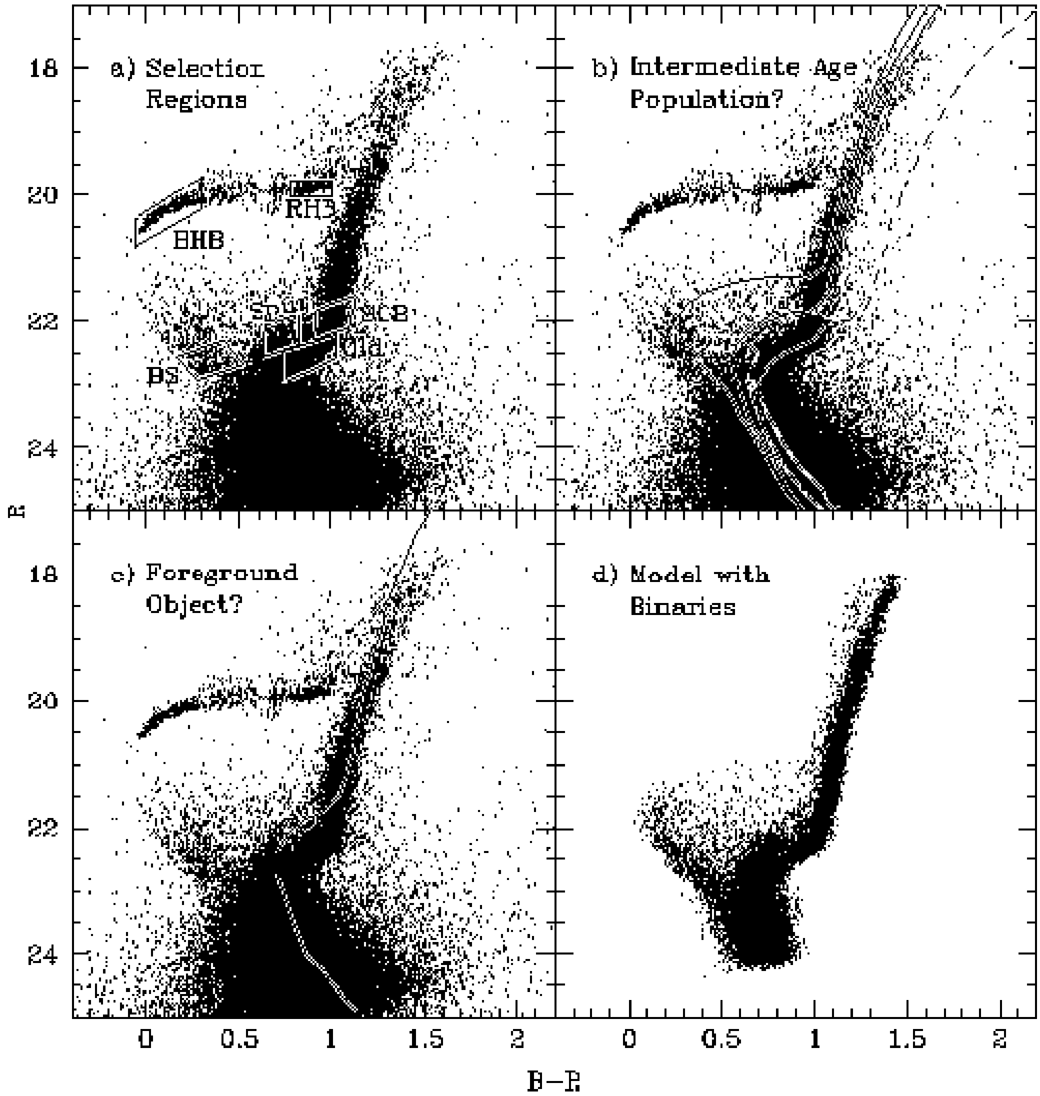


Table 1: Star Counts and Count Ratios

Counts						
	BHB	RHB	BS	Spur	SGB	Old
inner	309	275	297	549	1038	2671
outer	62	9	33	36	174	369

Count Ratios					
	RHB/SGB	BHB/SGB	BS/SGB	Spur/SGB	RHB/Spur
inner	0.26±0.02	0.30±0.02	0.29±0.02	0.53±0.03	0.50±0.04
outer	0.05±0.02	0.36±0.05	0.19±0.04	0.21±0.04	0.25±0.09
Δ[a]	7.4σ	1.1σ	2.2σ	6.4σ	2.5σ
$T2$[b]	6.4	1.8	2.9	8.8	3.6

[a] $\Delta = \frac{|R_{inner} - R_{outer}|}{\sqrt{\sigma^2_{R_{inner}} + \sigma^2_{R_{outer}}}}$, where R is the star-count ratio in consideration.

[b] see Da Costa et al. 1996 for a definition of the T2 statistic